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13. ABSTRACT *(Maximum 200 words)*

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The purpose of using these fuels was to investigate: additive effects on the (invisible) preflame reaction and visible premixed flame development; flame behaviors of bio-Diesel fuels; CN effects on in-cylinder reactions; and others. There is some evidence that the formation of the visible flame kernels may not be directly related to the preflame reactions when the additive is used to increase CN. The reactions during the ignition delay of bio-Diesel fuels were rather unpredictable, therefore requiring additional investigation. Among the most indicative timelines for determining a fuel's CN were those of: the maximum dp/dt; the start of pressure rise; the first premixed flame; and the peak pressure. The timeline of maximum dp/dt seems to be most insensitive to the variation of injection timing. Some new findings are also reported in the paper.

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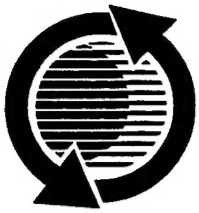

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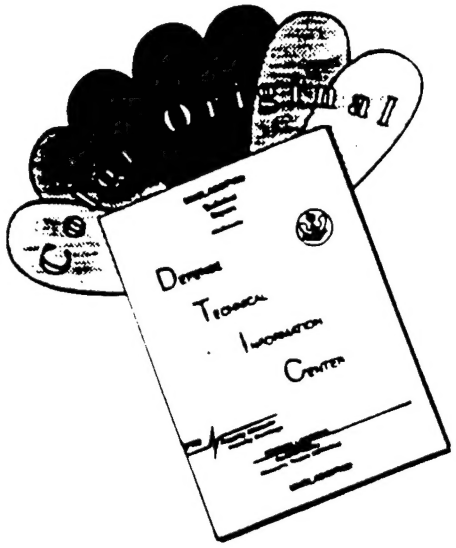

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Fuel Effects on Diesel Combustion Processes

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Abstract

The crank angle locations for the *first occurrences* of several main combustion events in a Diesel engine were investigated for varied fuel parameters. The events studied include: preflame reactions; premixed flame propagation; start of pressure rise; maximum rate of pressure rise (dp/dt); and peak cylinder pressure. The fuels employed in the study were in two groups: (1) Base fuel-1 and derivatives prepared by mixing it with small doses of a cetane number (CN) enhancing additive; and (2) Base fuel-2 and those made by adding different amounts of bio-Diesel fuel.

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Introduction

In addition to the physical processes, progressive invisible chemical reactions precede the abrupt flame propagation and rapid rise of pressure in a Diesel combustion chamber. These preceding reactions produce many different intermediate species presumably to play respective roles in the subsequent self-ignition and heat-releasing reactions. Much has been studied on these low-temperature kinetics-controlled elementary reactions for various simple fuels under similar reaction environments. However, because of the yet insufficient knowledge of the reaction mechanism of complex Diesel fuels (and the effects of physical events) in the spray during the ignition delay period, at present even the time when the chemical reactions actually commence during this period is not well understood. The reaction starting time, therefore, is not properly considered in the state-of-the-art computer models, which would be a key for implementing the formation kinetics of species in various applications, such as an accurate prediction of NOx and soot emissions. It is pointed out that since a great portion of modern Diesel engines are equipped with a high-pressure (electronically controlled) injection unit, the time period dictated by the physical processes may become insignificant for such systems.

This brief review illustrates the importance of determining the fuel's chemical tendency of initiating-propagating reactions in the compression-ignition (CI) environment. At present, the most widely accepted criterion for these fuel characteristics is cetane number (CN), a reference quantity evaluated based on the ignition delay, the time period from the start of injection to the first *visible* flame front or the start of *pressure rise*. Discussing the CN of a fuel, which is evaluated in reference to self-ignition characteristics of a mixture (of hexadecane and heptamethylnonane), some aberrant fuel formulations may not suit this traditional definition. Two such examples are brought up here, i.e., bio-Diesel fuels and fuels containing a CN-enhancing additives (CN booster).

While the molecular structure and bond energies of the fuel may help us understand how readily a fuel is decomposed to produce elementary species for preflame reactions, it remains debatable if the time period prior to

occurrence of the in-cylinder events is significantly affected by physical properties of fuel. It is particularly relevant when they are greatly modified, such as when a bio-derived fuel having unusually high-viscosity is mixed with the conventional Diesel fuel, which would modify the spray pattern and vaporization of the fuel. In other words, the addition of such a new fuel would not only changes the chemistry of reactions to affect the onset of the self-ignition (i.e., the crank angle degree, CA when the first visible self-igniton kernel appears, which is called hereafter as the *timeline* of visible flame) but also alters the physical processes within the plume, which would affect the timeline of the former. If this is the case, the injector characteristics affecting the physical processes will have to be considered in defining a fuel's CN. This may be further exemplified by the differences in spray formation via the conventional (low-pressure) injector and the new high-pressure injector. The next example involves the use of a fuel additive introduced to the base Diesel fuel in fractions of one percent in order to increase the CN. Since a small amount of additive will minimally modify physical characteristics of the mixture, this would rule out the physical effects on the CN. What is unknown, however, is whether the additive alters the overall chemical kinetics of hydrocarbon species of the base fuel, by hastening/multiplying most preflame elementary reactions, to cause an earlier visible flame, or if it simply produces abrupt explosive centers in the mixture, by "infusing" new complemental or separate reactions (in addition to those expected without the additive).

Additionally in the preflame reactions, unlike the flame initiation in spark ignition (SI) engines made directly on the fuel-air mixture by a single electric arc, the first visible flame kernel in the CI is a result of progressive thermo-chemical reactions occurring during the ignition delay. This kernel is not the sole center of the reaction propagation throughout the chamber, but there are numerous such reaction centers (within vaporized portions of the fuel spray) nearly equally "cooked" so as to be consumed almost simultaneously at the end of the ignition delay. The extent of preflame reactions, therefore, would dictate not only how early and explosively the premixed flame occurs but also the postflame products formation. These processes, therefore, affect the heat release characteristics dictating the thermal efficiency and the species formation determining the exhaust emissions.

However plausible the above argument as to the preflame reactions may sound, it was only within the recent year that the first tangible and illustrative evidence of the preflame reactions taking place in Diesel combustion were captured [1].* This study reported spectral images obtained from a direct injection (DI) CI engine with optical access by using Rutgers high-speed multispectral infrared (IR) digital imaging system. The method was to capture a set of four geometrically identical images in respective spectral bands at successive instants of time during both the periods of ignition delay and combustion reaction. The spectral bands in the study were chosen to capture radiations from different species formed in the fuel spray. They included one image

*Numbers in parentheses designate references at end of paper.

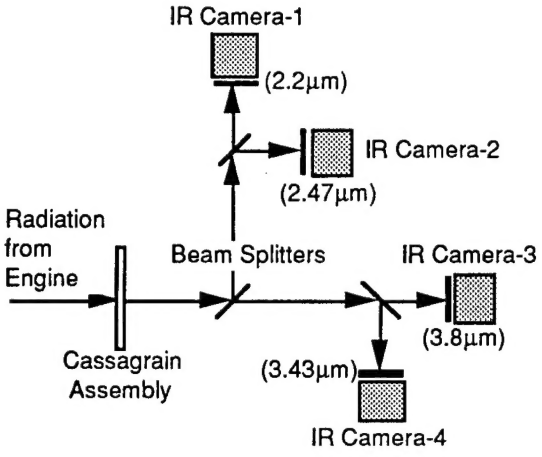


Fig. 1. Schematic Presentation of Rutgers SIS.

mainly exhibiting (visible) radiations from water vapor (and soot) and another showing (invisible) radiation from intermediate species. The "intermediate" precursors of the visible reaction products is pronounced here because their images were captured in a particular band during the ignition delay period, which discovery further motivated the present study. Note that images of similar preflame reactions were also observed via the same spectral band in an SI engine [2].

In the present study, in order to obtain a better understanding of the reactions during the ignition delay period, which is considered to be affected by both chemical characteristics and physical properties of the fuel, seven different fuels, including two different base fuels, were used. The first base fuel was mixed with small amounts of a CN booster and the second base fuel was blended with different amounts of bio-Diesel fuels.

Experiment

Since the present study was performed after obtaining the findings from the earlier work [1], the same apparatus were used. They include (1) high-speed multispectral IR imaging system and (2) Diesel engine with optical access, which will be only briefly described here. More details may be found elsewhere [1-4]. Note that the engine was equipped with an electronically-controlled high-pressure injection (HPI) system.

Multispectral IR Imaging System. This is a one-of-a-kind system newly designed and fabricated at Rutgers University [1-2,4], which is referred to as the Rutgers System or Super Imaging System (SIS). As shown in Fig. 1, this SIS has four units of high-speed IR digital cameras connected to a single optical unit. The radiation from the optical access of the engine is collected by a cassegrain assembly consisting of two concave mirrors, and the radiation is then relayed through three different spectral beam splitters. This arrangement produces four geometrically identical (pixel-to-pixel matching) images in respective spectral domains. A narrow band filter installed in front of each camera (indicated by the central wavelength

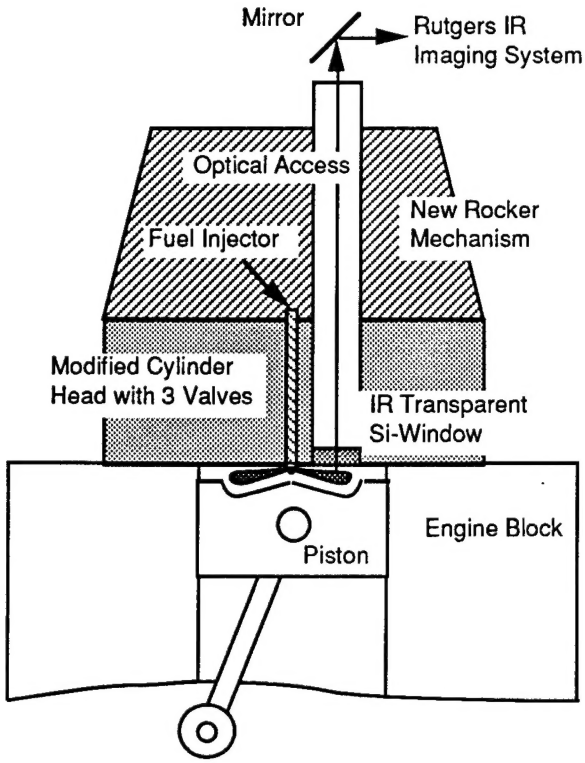


Fig. 2. Schematic Presentation of the Single Cylinder Engine Mounted by a Cummins 903 Cylinder Head with Optical Access for the SIS or Rutgers IR System.

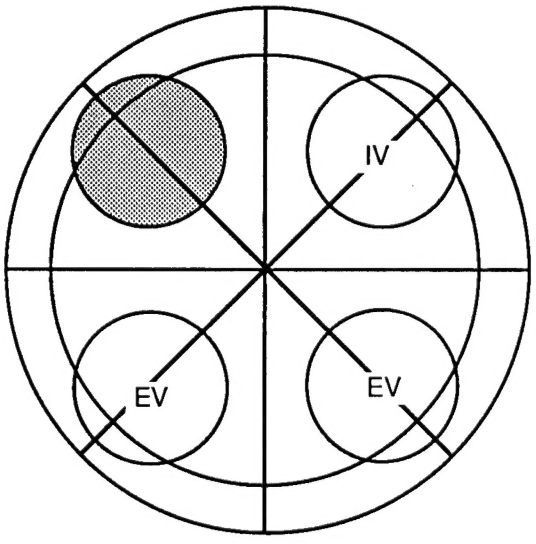


Fig. 3. Optical Access (shaded area) with respect to Spray Plume Axes.

in Fig. 1.) further specifies, within the corresponding domain, the spectral nature of the image upon the camera.

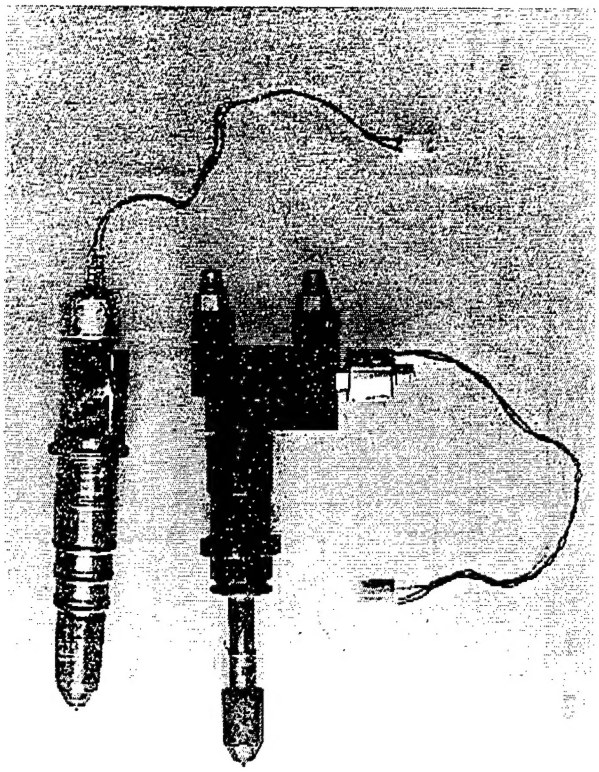
Among the performance features of the SIS having Pt-Si imagers (64x128 pixels each) in the camera are: imaging rate as high as 1,800frames/sec per camera; independently variable exposure period as short as 20μsec; spectral range of 1.5-5.5μm; and total 256 images to be captured (in each experiment) per camera. The cameras in the SIS are simultaneously operated according to the predetermined setting, including: the exposure period; the total number of images to be obtained per cycle; the start of imaging (in CA) with respect to a reference marker (here, top-dead-center, TDC); and the interval between successive images in CA.

Four spectral images simultaneously obtained by the SIS at successive instants of time implies that, when they are captured in spectrally discriminating manner, ideally as many as four difference pieces of information per corresponding pixels at the CA may be obtained. Upon properly processing the raw data, quantitative imaging may be achieved such as distributions of temperature, and concentrations of water vapor and soot. While new methods of such quantitative imaging are being developed in Rutgers, it is found that raw images produced by the SIS permit finding new pieces of in-cylinder information, which are difficult to obtain by using the conventional diagnostic devices.

Engine Apparatus. A single-cylinder DI-CI engine was constructed in collaboration with Power Energy International (Madison, WI) and BKM, Inc. (San Diego, CA), under a sponsorship of the U.S. Department of Defense University Research Initiative [3]. The engine body was constructed to accommodate components from a Cummins 903 engine. In this new single-cylinder arrangement, the engine (Fig. 2) uses a section of the 903 cylinder head to obtain representative characteristics of the DI-CI engine population.

Some modifications were made on the Cummins engine cylinder head for installing an IR optical window: conversion of one of the intake valves to make room for the optical access; a new rocker-arm mechanism, which provided a cylindrical space for the optical passage; a pressure transducer installed flush with the chamber wall; a measure to use either a Cummins (mechanical) PT unit injector or BKM's Servojet electronic-controlled HPI injector. The optical access (with viewing area of 37mm diameter) was made barely big enough to cover the projected view of a spray plume out of an eight-hole (0.15mm diameter) nozzle, which assumes all spray plumes to be identical to each other. Figure 3 shows the axes of plumes with respect to the (imaging) optical access, which will be referred to when the in-cylinder spectral IR images are discussed later. Additional engine information may be found elsewhere [1,3].

High-Pressure Injection. The electronically controlled HPI system which replaced the Cummins PT type injector in our 903 engine for the present study was basically a Servojet unit injector of the accumulator type [5]. Because of the crowded engine cylinder head due to new installation of an optical access and a pressure transducer (in addition to the existing components such as the valve train), the relatively bulky Servojet unit was not usable in the apparatus. Keeping the original system design features, an entirely new injector unit was fabricated in our laboratory:



(A) (B)

Fig. 4. Electronic-controlled High-pressure Injectors: (A) Rutgers-built Unit and (B) Original BKM Unit.

Among the key considerations taken into account for this new unit was to use original injector tips of the Cummins PT nozzle, which was to provide technical and economic flexibility in choosing different injector tip geometries. The operation of the injector was performed by using the same electronic package given with the original Servojet unit. The high-pressure injection is achieved by an intensifier (1:16 ratio) in this HIP system to have as high as 165MPa (24,000psi, or 24Ksi)). The cut-off pressure of injection is approximately 10Ksi. Figure 4 shows the injectors: The original injector provided by BKM is on the right and the new unit built at Rutgers is on the left. Note the end portion of the new injector is from the Cummins PT nozzle.

An extensive bench-top characterization of this new injector package was performed prior to in-cylinder measurement. This was necessary to determine several important pieces of information about the new HPI, including the relationships of the actual start of fuel injection and the amount of fuel injected per cycle to the input control by the electronic signals, i.e., the pulse width and timing, and the accumulator pressure, respectively. It is pointed out that the time of injection was defined as the time when the fuel plume tip reached a sensor located about 10mm away from the injector nozzle hole. The injection (sac) pressure-time history was not measured in the present characterization, but is inferred to be the same as the original unit [5], which resembles a spike-shape that collapses rapidly to have a very short residual period of low injection pressure.

Fuels. Seven different fuels were used in the present work, as shown below (Table-I). The fuels in Group-1 were provided by Ethyl Corporation by mixing the base fuel-1 with respective amounts of an Ethyl additive known as Hess F9349 (boiling point, 153^{o}C) to obtain different CNs, as indicated in the table. Note that these fuels have different CNs with physical characteristics kept about the same. In the table, "Plot" indicates the presentation of data together on the same plane in figures shown later.

Table-1. Fuels Studied and Data Plots

Fuels	Contains (vol %)	Cetane No.	Plot
Fuel -1b	1.00 Hess F9349	70.8	
Fuel -1a	0.25 Hess F9349	60.1	
Fuel -1	0.0 (Base fuel-1)	51.6	(I)
Fuel -2	0.0 (Base fuel-2)	45.4	
Fuel -2a	20 Soy	Unknown	
Fuel -2b	40 Soy	Unknown	(II)
Fuel -2c	20 Soy & 20 Alkylate	Unknown	

The fuels in Group-2 were prepared at BDM (Bartlesville, OK) by mixing the base fuel-2 with respective amounts of an esterified soy oil (namely, bio-fuel) and alkylate, which is known to have CN of around 30. These fuels are expected to exhibit different behaviors in both the physical and chemical processes, particularly during the ignition delay period.

Results and Discussion

The core measurements in the present study include spectral IR images (in spectral bands of 2.2, 2.47, 3.43, and 3.8μm) simultaneously obtained at successive instants of time from a fuel spray plume during the ignition delay and combustion periods, and the pressure-time (p-t) data recorded at the same time. The measurement was performed with various injection times, namely 24.5, 18.5, 12.0, 9.0 and 6.0 bTDC. The engine was operated at 500rpm under a warmed condition throughout the entire experiment.

Nearly 1,000 sets of data were collected with some twenty cycles per condition in order to obtain a representative result for each. Since they were all gathered in digital form, this large amount of data was processed using several computer programs to determine important timelines of the Diesel combustion. They are periods from the start of injection to several consecutive events and a few new terms determined as some of the intervals:

(1) First (invisible) preflame image;
(2) First (visible) premixed flame image;
(3) Start of pressure rise;
(4) Maximum dp/dt;
(5) Peak pressure;
(6) First preflame image - first visible flame image;
(7) First visible flame - start of pressure rise, and
(8) Start of pressure rise - maximum dp/dt.

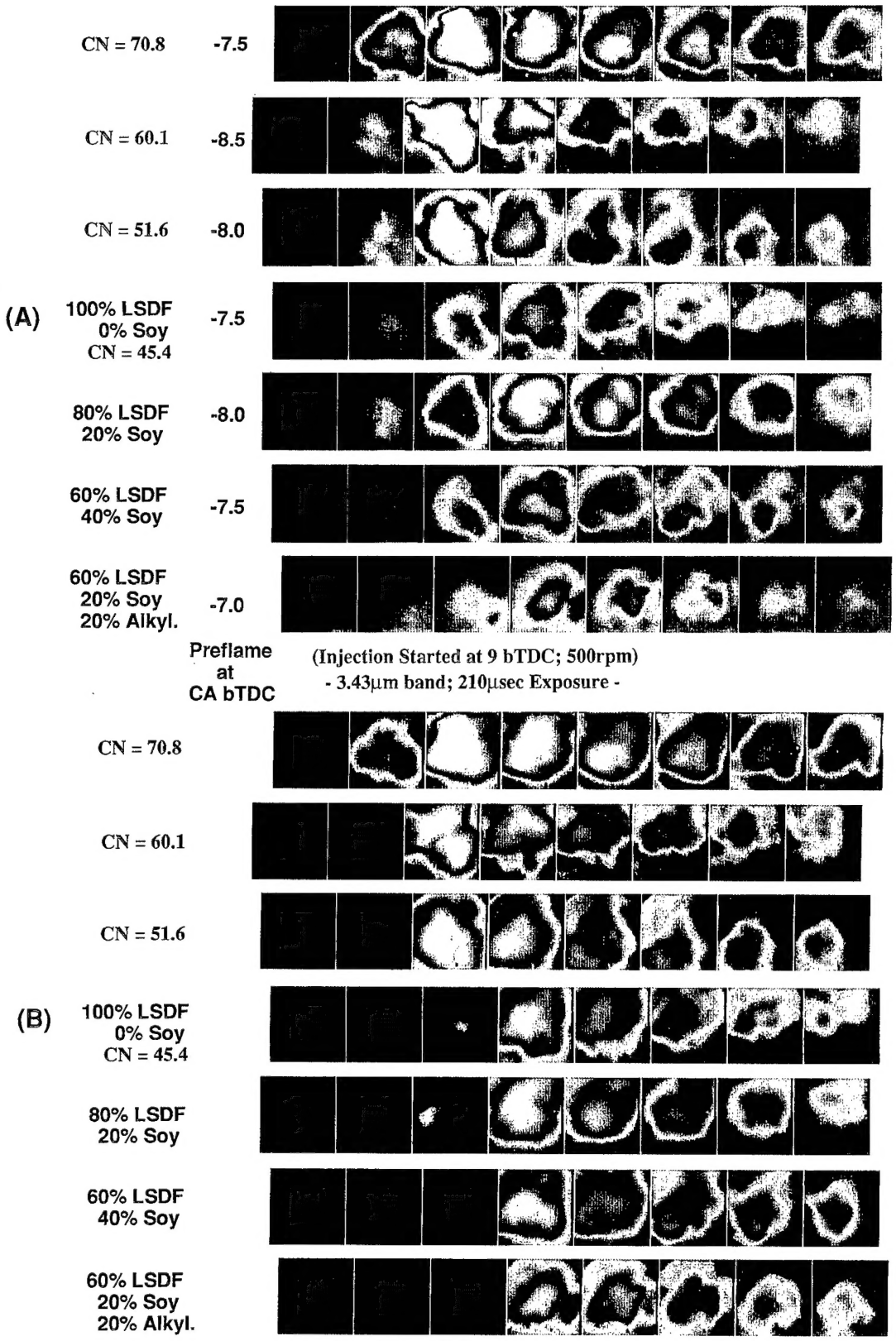


Fig. 5-(A). High-speed Spectral IR Images of Diesel Flame in 3.43μm.
(Starting with First Preflame Images for Individual Fuels)
-(B). High-speed Spectral IR Images of Diesel Flame in 2.2μm.
(Visible Flame Images Simultaneously obtained as 8-(A))

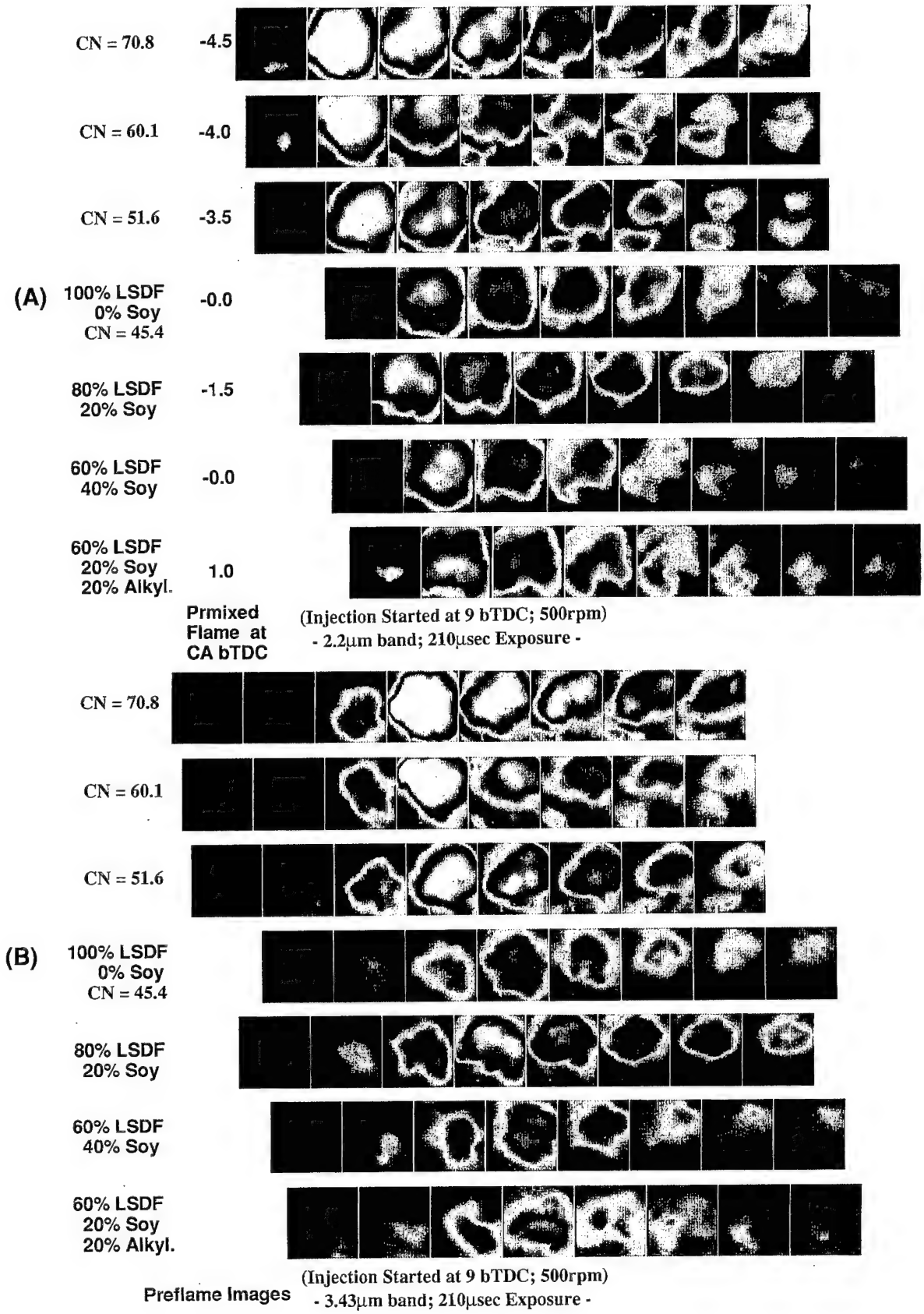


Fig. 6-(A). High-speed Spectral IR Images of Diesel Flame in 2.2μm.
(Starting with First Visible Flame Images for Individual Fuels)
-(B). High-speed Spectral IR Images of Diesel Flame in 3.43μm.
(Preflame Images Simultaneously obtained as 9-(A))

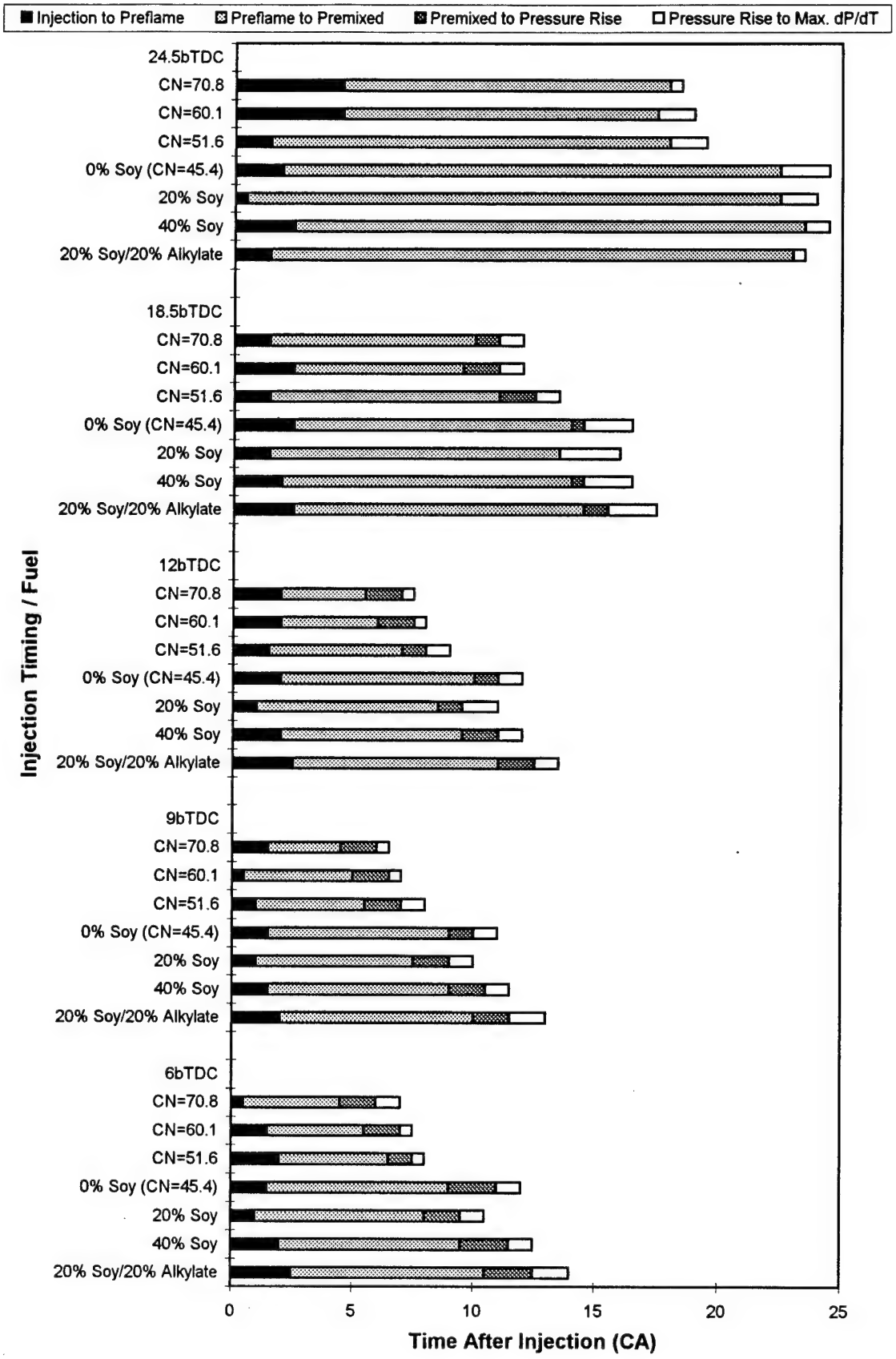


Fig. 7. Effects of Fuels on In-cylinder Reactions in a CI Engine Cylinder.

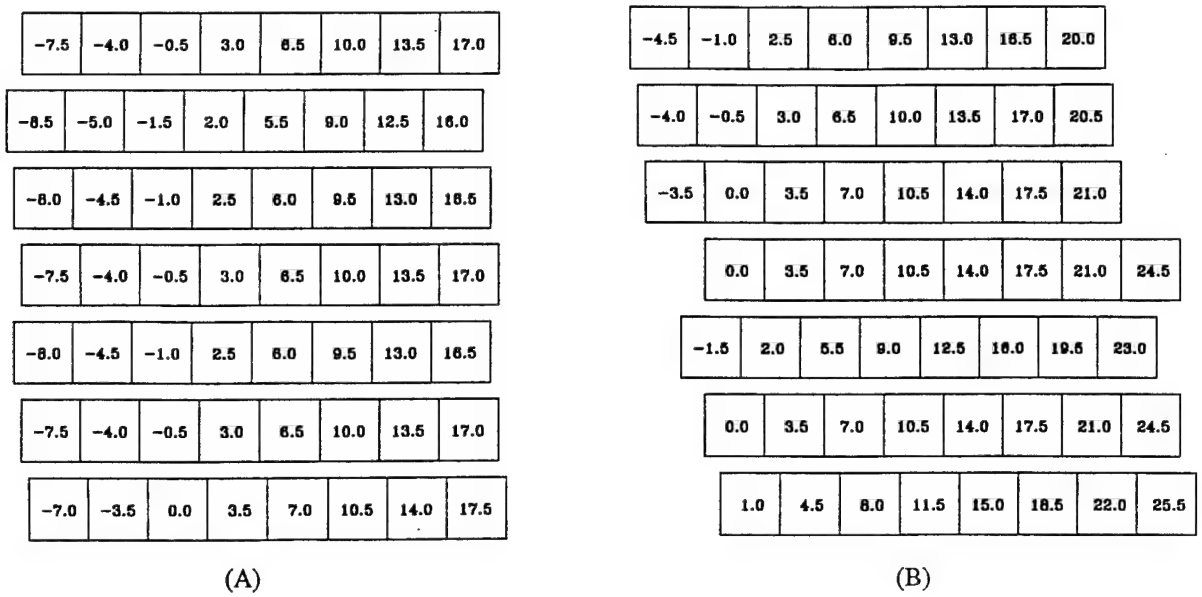


Fig. 8. Look-up Tables for High-speed Images to Indicate each Time of Imaging: (A) for Fig. 5 and (B) for Fig. 6.

The timelines of those events were measured with a temporal resolution as fine as a 0.5CA increment. Finding those of preflame and premixed flame, the feature of the SIS of varying the start of imaging (after a preset period, in temporal resolution of 0.5CA, from the reference marker, e.g TDC of the previous revolution) was utilized. After an engine condition was set forth, the start of imaging was varied back and forth until a barely detectable preflame image was found in the set of successive images, and the very CA when this image obtained was used for determining the timeline of preflame. The next images followed thereafter in every 3.5CA-interval in this experiment. Some sample results are displayed in Figs. 5 and 6. They are shown in pseudo-color in order to illustrate the local variations by displaying the digital results. Other events in p-t data were determined by using the computer programs as mentioned earlier, which is not elaborated here.

The overall results are summarized in Fig. 7. The timelines are illustrated in a relative scale representing CA periods in a self-explanatory manner. For example, the peak value in each column represent the period from the injection to the CA when the peak dp/dt occurred. Since this summary picture is highly crowded, individual timelines are separately plotted in Figs. 9-13.

In those plots, for an obvious reason of putting together results with varied CN as seen from Table-1, Plot-(I) includes those from the fuels of Group-1 and the base fuel from Group-2, as presented in the upper portion of each figure. Plot-(II) contains results from the fuels in Group-2 separately, as shown in the lower portion of the same figure.

Spectral IR Images. In order to determine the timelines of preflame and premixed flame, a set of spectral images was simultaneously obtained of both (invisible) preflame reactions (in 3.43μm band) and (visible) premixed flames (in 2.2μm band), plus those in 3.8 and 2.47μm bands. For example, looking at Fig. 5-(A), which was obtained with the injection starting at 9bTDC, the numbers in the second column indicate the CA when the first preflame was captured. A look-up table (LUT) for this figure is included for convenience of discussion in Fig. 8-(A). The rows of successive images for different fuels are arranged in a relative time-scale, with the far left indicating CA exhibiting the earliest preflame. Figure 5-(B) shows sets of (visible) premixed flame images simultaneously obtained at the corresponding CAs.

After completing this experiment, in order to determine the CA when the first premixed flame was captured, the same as above was performed, but at this time by finding the first visible image from the successive images in 2.2μm band, as shown in Fig. 6-(A). A matching LUT is included in Fig. 8-(B). At this time, the corresponding images via 3.43μm band was also obtained to investigate the development of the preflame under the same condition.

Comparing images at corresponding CA in Figs. 5 and 6, while there is strong radiation in 3.43μm band (with no radiation seen in 2.2μm band), no measurable change in p-t from that of a warm-engine motoring condition was found. This indicates that the observed preflame reactions make no impact on the heat budget. The preflame image, therefore, was suggested to be of chemiluminescence from some intermediate species including OH radical and aldehydes [1,2].

Fuels with Varied Amounts of Additives. First, figures labeled by (A) showing results from fuels with varied CN, the upper or right-side portion of each figure, is discussed. Note that those indicated by (B) with results on fuels mixed with varied amounts of bio-Diesel fuel is discussed later. The timelines of preflame and premixed flame are summarized in Fig. 9: Except for the very early starts of injection, i.e., 24.5 and 18.5bTDC, the ignition delay measurements (determined by the visible premixed flame) seem reasonable, the higher the CN, the shorter the

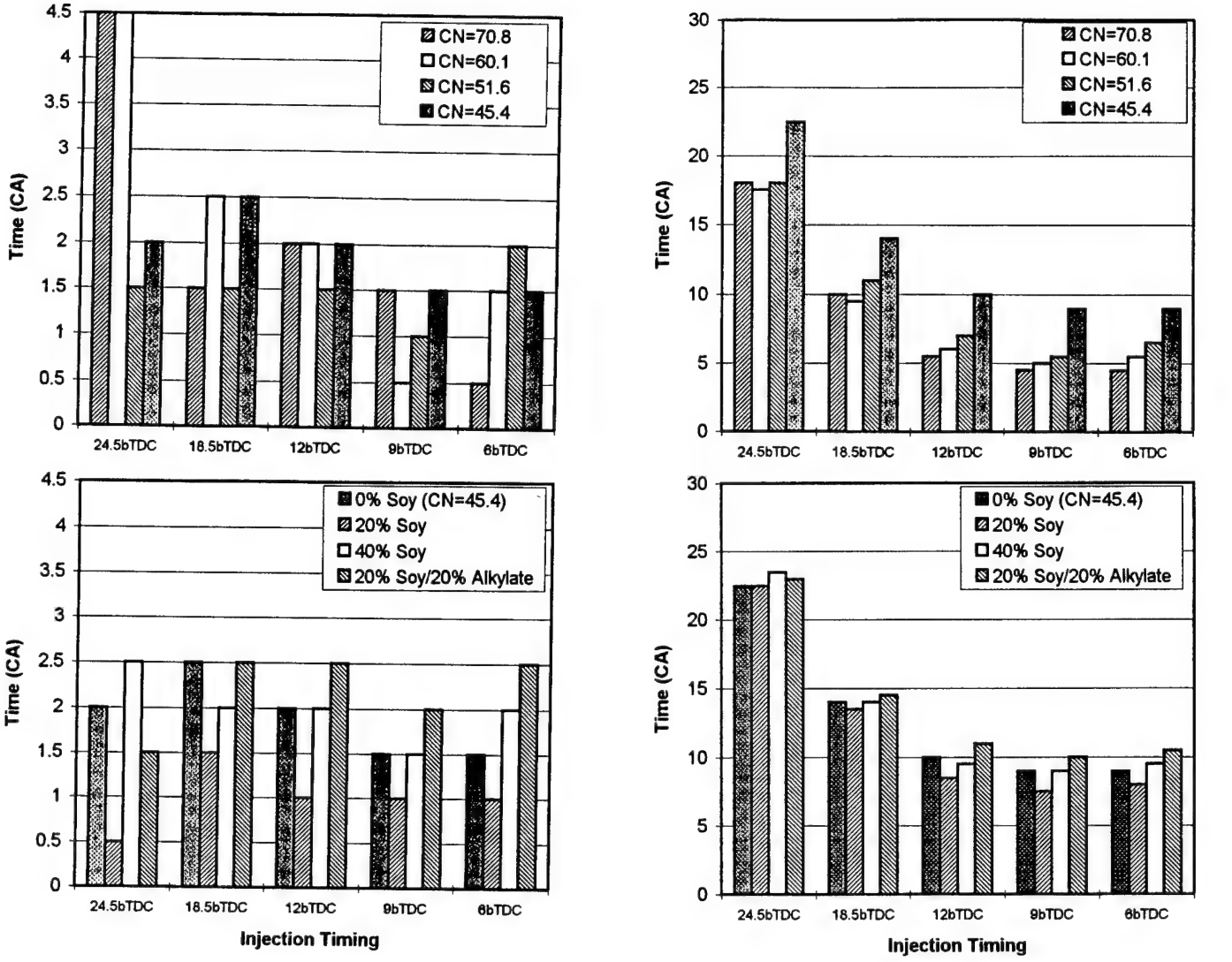


Fig. 9. Fuel Effects on Time from Injection: (A) to First Preflame Image, and (B) to First Visible Premixed Combustion.

ignition delay. This is similarly found from the timeline of the start of pressure rise obtained from p-t data as summarized in Fig. 10-(A). In addition, the timelines for the maximum dp/dt and the peak pressure are also included in Fig. 10-(B) and Fig. 11, respectively.

It is noteworthy from a comparison of Figs. 9, 10 and 11 to find that the timelines of maximum dp/dt and the start of pressure rise (preferably the former) may be the best indicator of all in determining the CN, because they appear to be *independent of the injection time*. In other words, these timelines may be most insensitive to variation of the reaction condition at the time of injection, and this warrants further study. If it is the case, the timeline of maximum dp/dt would be the more reliable indicator than the traditional defining method, particularly when the CN of fuels are determined by using a constant-volume bomb (instead of using the real-world engines). This is because a bench-top bomb apparatus may not exactly duplicate the same environment as in an actual Diesel engine cylinder at the end of compression.

Looking at Fig. 9, a couple of significant findings may be listed: They are: (1) the preflame reaction starts almost immediately after the start of fuel injection; and (2) there seems to be little difference in its timeline for fuels even with a wide variation of CN. Discussing the first, let's consider the CI environment. When the Diesel fuel containing components having self-ignition temperatures of lower than 500K is injected into compressed air at over 800K, it may not be difficult to expect some chemical reactions to occur without a significant (physical) delay. In particular, when the fuel is injected by an HPI of over 160MPa, the fuel plume will have finely disintegrated droplets vaporizing almost instantly to minimize any delay prior to commencing chemical reactions emitting chemiluminescent radiation.

Discussing the second finding, the change in the timeline of preflame is rather random and very small at best. Particularly, those for fuels with CN of 70.8, 60.1 and 51.6 are very small, which are results of mixing the base fuel with

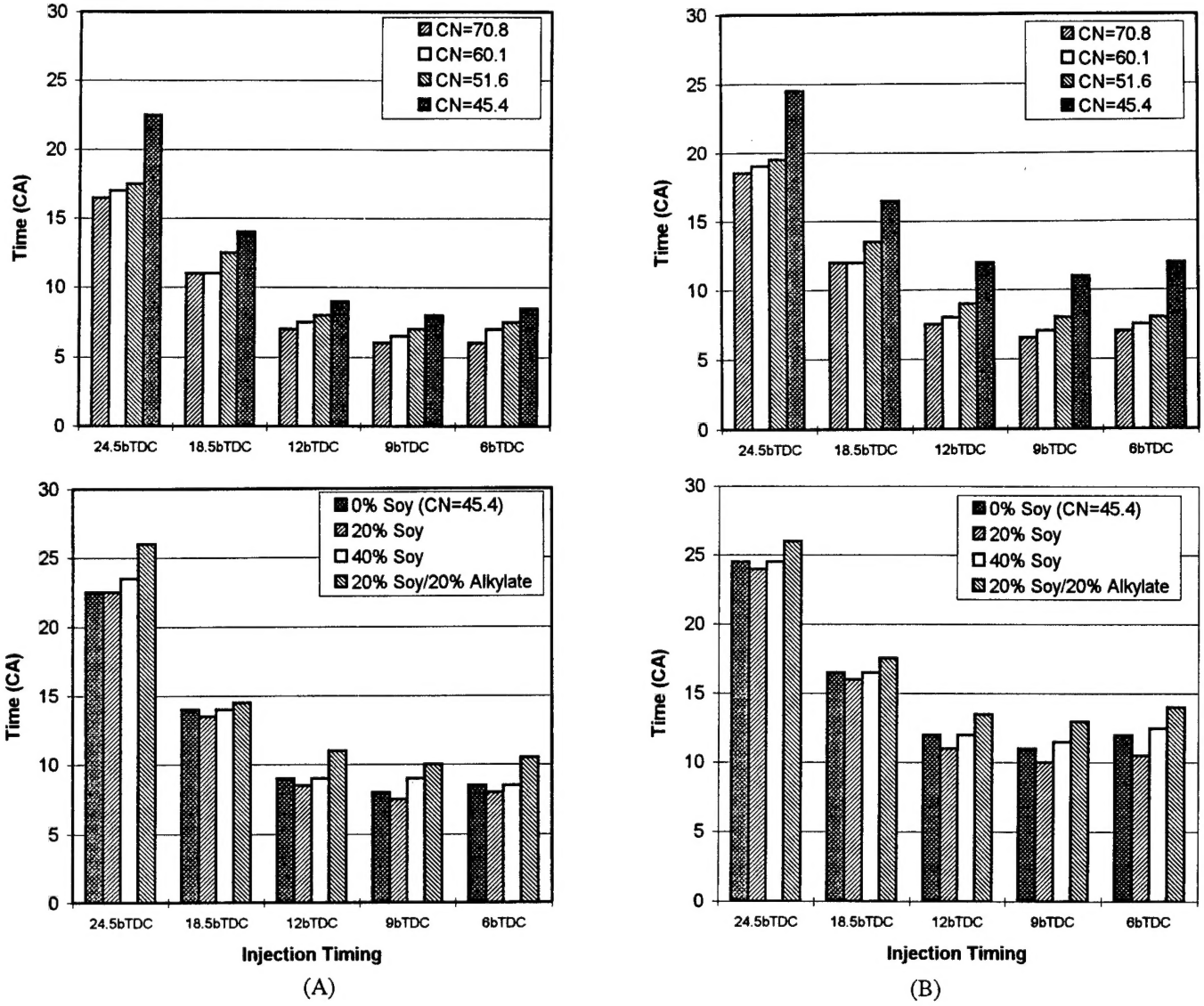


Fig. 10. Variation of Time from Injection: (A) to Rapid Pressure Rise and (B) to Maximum dP/dt.

small amounts of the additive, respectively. Except for the very late injection, the difference in the timelines of two base fuels (with CN of 51.6 and 45.4) appears to be more obvious and seemingly predictable than the above having bigger CN differences (achieved by an additive). It may be due to the fact that the difference in CN between these two base fuels was solely from the fuel characteristics, while the above was changed by mixing of an additive. The former observation suggests that the additive may not affect the preflame reactions, which seems to be reasonable in view of the consideration mentioned earlier. That is, since the amounts of the additives is so small that they are not expected to alter the formation of species as a result of the decomposition of the base fuel hydrocarbons as dictated via low-temperature kinetics. One the other hand, looking at Plot-(I) for the timeline of premixed flame shown in Fig. 9-(B), which is a traditional criterion determining CN, the additive resulted in what was expected. Recall that the onset of premixed flame accompanied by a rise of pressure is a result of thermal imbalance, when the high-temperature kinetics takes over the reaction routes. Putting these facts together, one may suspect that the role of the additive in the CI environment may be more to affect high-temperature kinetics, perhaps by infusing new exothermic reactions and or accelerating some key elementary reaction to such processes, which, without the CN booster, are not expected to occur to drive the mixture to a thermal imbalance stage sooner.

Fuels Containing Bio-Diesel Fuel. The lower or right-side portion of each figure, Plot-(II) contains results from fuels prepared by mixing the base fuel-2 with different amounts of bio-Diesel fuel. The timelines of both the preflame and premixed flame for fuels in Group-2 are rather unpredictable, compared with the same with those in Group-1. In general, addition of esterified soy (hereafter called, "soy") to a base fuel causes an increased CN, which seems reasonable when the base fuel and fuel containing 20% soy (Fig. 9) are compared with each other. What is quite

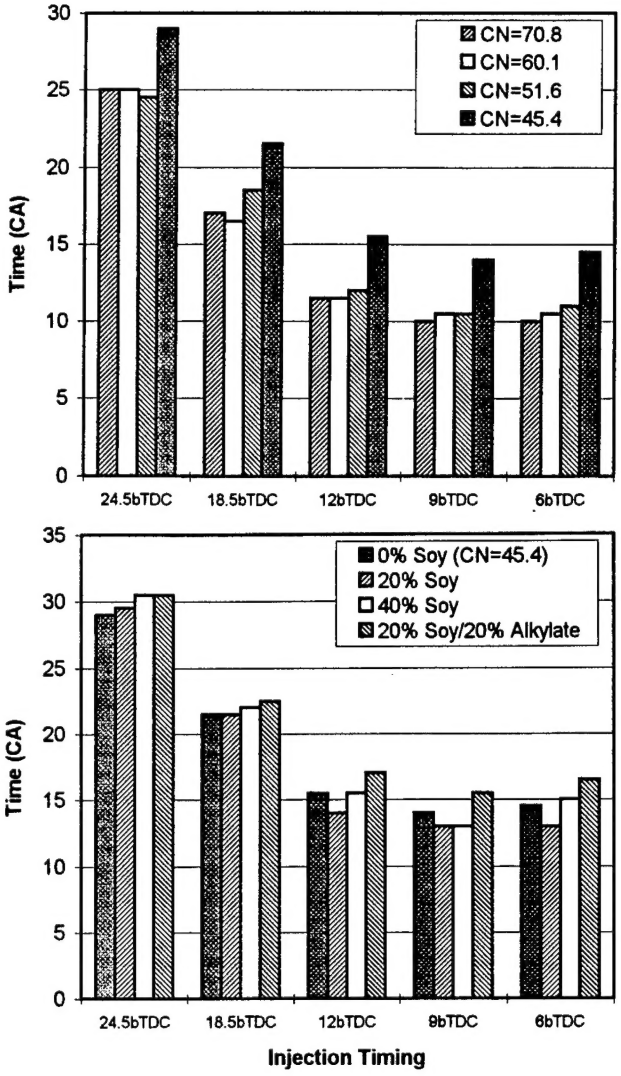


Fig. 11. Time from Injection to Peak Pressure Affected by Fuel.

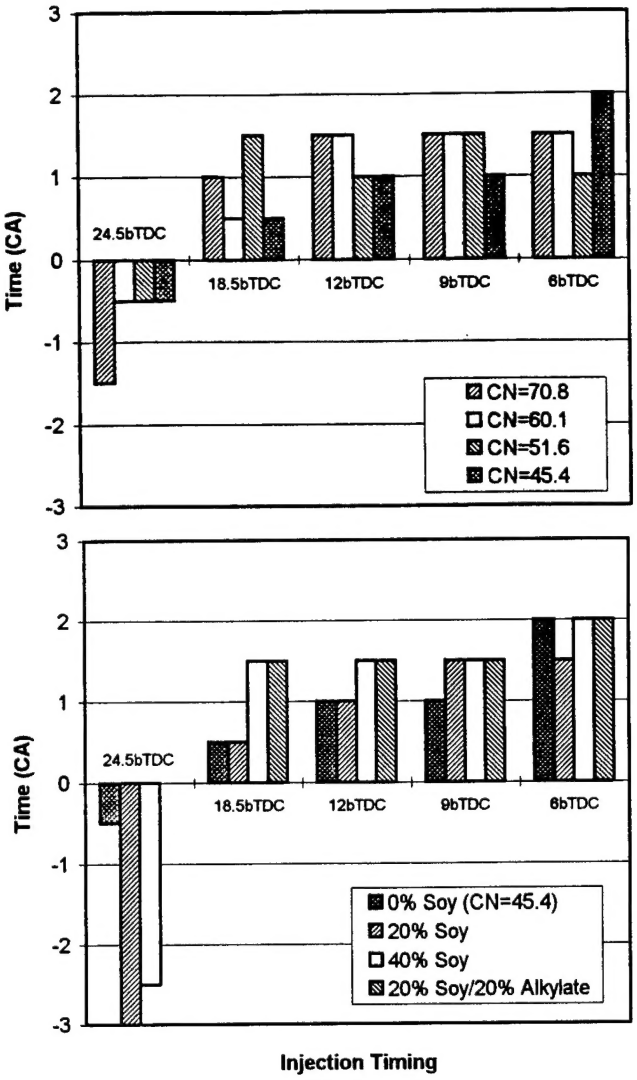


Fig. 12. Time Period from First Visible Premixed Combustion to Start of Rapid Pressure Rise.

unexpected is the fuel containing 40% soy, which behaved almost like the base fuel. Even radiation characteristics appear to be similar to each other (see Figs. 5 and 6). A possible reason for this unusual finding may be that the spray pattern is so greatly modified (by the physical role of viscous bio-fuel) to cause such a result, which is a marginally convincing interpretation at best calling for an additional study. Mentioning fuel-2c containing 20% soy and 20% alkylate, the trend was expected because the CN of this alkylate is around 30, which would lengthen the ignition delay. This suggests that the small effect of soy addition of shortening the ignition delay is offset by the alkylate's role of the opposite effect.

Ignition Delay and Combustion by Other Timelines. In addition to the timeline of premixed flame used for determining the ignition delay, those for the start of pressure rise, the maximum dp/dt, and the peak pressure are also considered (Figs. 10 and 11). Since the net energy release as the result of ignition is reflected by the start of pressure rise (compared with that of a warm-engine motoring operation), its timeline is also being used for evaluating CN. This timeline, however, does have some measurable differences from that of premixed flame as shown in Fig. 12, generally occurring later than the latter. This is considered to occur due to heat loss via several possible ways, including: the latent heat of liquid fuel vaporization, continuing endothermic chemical reactions in the plume, and heat transfer to the wall. There is an illustrative trend in both plots that the later the injection time, the longer the period from the first flame to the start of pressure rise, which seems to suggest the wall heat loss may not be a decisive possibility. A possible explanation is that the fuels having the same base fuel (even with big differences in CN) may have almost an identical difference between the timelines (for respective injection times).

When the fuel was injected very early, however, the trend was opposite, i.e., the visible flame was observed after the pressure rise was measured, which was most significant for fuel containing 40% soy, and that with 20% soy plus

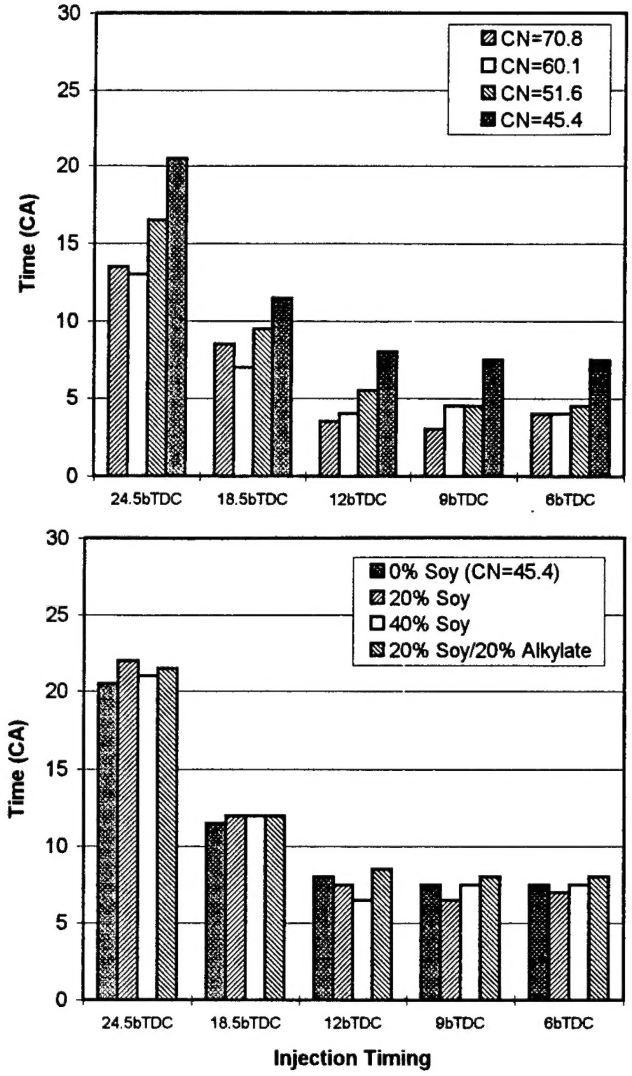


Fig. 13. Time Period from Preflame to Premixed Combustion.

20% alkylate. The only possible reason for this is that there were invisible exothermic reactions in the cylinder causing an early pressure rise. Without offering a convincing explanation, one may wonder if the unusual ignition behavior for fuel with 40% soy, as explained above, is related to this peculiar result. This seems to also support the argument on the probable limitations in using a constant-volume bomb to determine the fuel's CN, as discussed earlier.

Preflame Development. First, since the time period having preflame reactions prior to the premixed flame is expected to indicate how the intermediate species continue to build up prior to the onset of abrupt ignition, Fig. 13 is included here. Looking at Plot-(I), the result is quite similar to the timeline for the premixed flame (Fig. 9), which, therefore, may be a criterion to be used for determining ignition quality.

Let's consider what is happening during this period: Reviewing preflame images in Fig, 5-(A) compared with the onset of premixed flame images in Fig. 5-(B), particularly images obtained at 0.5bTDC for fuel-2 (see LUT at Fig. 8-(A)). When the small section exhibiting weak premixed flame (Fig. 5-(B)) is made to overlap the corresponding preflame image in Fig. 5-(A), one may find that the latter seems to contain both zones of the preflame reaction and premixed flame. A similar finding may be made when the same is attempted on images at 1.0bTDC for fuel 2a (containing 20% soy). This observation was similarly found when those in Fig. 6 are compared in the same way. Note that Fig. 6-(B) will have to be placed ahead, by a period 7CA, of (A) in order to compare with each other. In general, the longer the period between the two timelines (of preflame reaction and premixed flame), the stronger the reaction size of preflame zone. What seems to be intriguing is that the zone having the first premixed flame development is not necessarily where the strongest preflame radiation is found. For example, locating the first premixed flame in Fig. 6-(B) and matching it with the corresponding preflame image in (A), one could list such, particularly from fuel 1b; fuel 1a and fuel 2c. Although this trend appeared to occur more in those containing the CN enhancing additive, one could expect that the additive may produce separate chemical reactions leading to premixed flame (instead of increasing over all species formation of base fuel). Also, the mutual inconsistency between two images in respective reaction regimes (also in different times of occurrence) may be due to the gas motions in the cylinder. That is, the reaction volumes exhibiting preflame radiations are moved around prior to being matured to cause ignition kernels, which is captured as the first premixed flame propagation.

Why More NOx and Lower Particulate by Bio-Diesel Fuels? In general, vehicle fleet tests indicate that the higher the soy content the higher the NOx emission and the lower the soot measurement. At first, an observation with the bio-Diesel fuel experiment is mentioned. The soot deposit on the cylinder-side surface of the optical window was much less when the fuels containing soy were used, and instead, the surface was often covered with thin film of liquid layer, which was not the case when the conventional fuel was used to observe the formation of dry soot deposit. This may indirectly show a low soot formation with the bio-Diesel fuel. The in-cylinder images may give some insight into the reasons for such exhaust measurements also. In general the lower the CN, the lower the radiation intensity (Figs. 5 and 6) indicating the low soot formation.

Several observations may be listed regarding the increase of NOx formation with bio-Diesel fuel: In Fig. 5-A, there is some trend of having a greater activity in preflame reactions with bio-Diesel fuels. And the more active (and longer) the preflame reactions (and period), the less intense the premixed flame radiation, which indicate the portion of diffusion flame reaction is less, which is expected to produce more NOx. This consideration, however, does not seem reasonable when images (Fig. 5-(A)) with fuel-2 and those from fuel-2a are compared each other, which needs further study. At present, it is to be fair to indicate no conclusive interpretation can be offered from the bio-Diesel fuel results.

Summary

The timelines of main events in a direct injection Diesel engine equipped with a high-pressure (electronically controlled) injection unit were determined with a high-speed spectral IR imaging system and p-t history. The engine was operated by using seven different fuels including two base fuels: the first group of fuels was prepared by mixing a base fuel with different doses of CN enhancing additive (CN booster) and the second group was made by adding the other base fuel with different amounts of esterified soy (bio-Diesel fuel). The experiment was performed for four different injection times with the engine speed maintained at 500rpm under warmed engine condition.

The timeline, the crank angle when the first evidence is exhibited of a main event, with respect to the start of fuel injection, was determined for the following: (1) preflame reactions; (2) premixed flame; (3) start of pressure rise; (4) maximum pressure rise rate (dp/dt); and (5) peak pressure. New questions and issues came up as much as new findings were made in the study. Some are summarized in the following:

(1) The timeline of preflame reaction seem to be a useful indicator in determining CN of Diesel fuels while it is otherwise for fuels containing a CN booster. This may be explained by an expectation that an addition of the additive to a base fuel may infuse new chemical reactions in addition to the elementary (chain) initiating-propagating reactions controlled by low temperature chemical kinetics leading to the exothermic reactions sooner.

(2) The timelines of premixed flame, start of pressure rise, maximum dp/dt and peak pressure may be all used for determining CN of Diesel fuels, but the time of maximum dp/dt appears to be most indicative regardless of injection time.

(3) The base fuel containing bio-Diesel fuel yielded some predictable results while they were opposite when its content become very high, e.g. 40% of soy. This may be attributed by the physical change of spray pattern by the addition of the new fuel. It is clear further investigation is warranted.

(4) The timeline of premixed flame and that of the pressure rise did not occur at the same time although both are traditionally used for determining CN. The former preceded the later by as much as a few CA, for which the difference became even greater with retarded injection times.

(5) When the injection time was very early, e.g. 25bTDC, the behavior of in-cylinder events became rather unpredictable. This may indicate the limitations of using constant-volume bench-top reactors for determining CN of a fuel because its self-ignition environment may not be duplicated of a typical Diesel engine condition.

In order to resolve some unanswered questions, it is recommended that Diesel fuels having varied CN without containing a CN booster be compared with corresponding results from the matching Diesel fuels prepared by using the additive.

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